## 21.6 A CMOS 2D Micro-Fluxgate Earth Magnetic Field Sensor with Digital Output

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A complete CMOS integrated microsystem for detecting the direction of the Earth's magnetic field (whose full-scale value is on the order of 60µT), including both sensor and electronic interface circuit, achieves 4° accuracy on the measured angle and provides digital output. The system is realized with the micromodule approach [1], for optimizing both the sensing device and the electronic interface circuit. The magnetic-field sensor, shown in Fig. 21.6.1, is an integrated micro-fluxgate, developed in a CMOS process [2-6], where the ferromagnetic core is realized as a post processing step by DC-magnetron sputtering [7] specifically developed in order to maintain the material's ferromagnetic properties. The resulting core has the same magnetic properties as the amorphous ferromagnetic material used for the target (Vitrovac 6025 X), but with a very small thickness (about 1µm), thus allowing us to reduce the power consumption required to excite the device. The micro-fluxgate is realized in a 0.5µm CMOS process with copper metal lines for the excitation coil and aluminium metal lines for the sensing coils. The total area of the planar copper excitation coil, with 5.5µm thickness, 71 turns and 12µm pitch (8µm metal width and 4µm spacing) is 1760×1760µm$^2$ and its resistance is about of 120Ω. While the total area for the aluminium sensing coils, with 1µm thickness, 1.4µm metal width, 1.6µm spacing and consisting of 66 turns, is 650×650µm$^2$, and their resistance is about of 1.84kΩ. Applying a triangular excitation current of 18mA peak at 100kHz achieves a magnetic sensitivity of about 0.45mV/µT, suitable for detecting the Earth's magnetic field (±60µT).

The CMOS integrated interface circuit is able to excite the sensor with the desired current, readout the signal from the sensing coils of the sensor, process it, and provide a digital output signal. Thanks to the high-voltage (up to 26V) output stage of the excitation circuit, this interface circuit can be used with different micro-fluxgate magnetic sensors even if they require a large current for the excitation coils. Moreover, in the read-out chain it is possible to set the gain of the channel according to the sensor output amplitude, thus allowing us to adapt the circuit to the sensitivity of the fluxgate device being used.

The block diagram of the whole system is shown in Fig. 21.6.2. The integrated interface circuit consists of three different parts: an excitation circuit, two readout channels (for the X and Y sensor outputs), and a 13b analog-to-digital converter. The excitation circuit is able to produce a triangular output current whose amplitude is customizable. This circuit is composed of two parts operating at 3.3V and 26V. The first block generates a square wave with frequency equal to 100kHz and programmable output amplitude, which is integrated in order to obtain a triangular waveform centered near half of the lower power supply. The second block consists of a high-voltage mirrored operational amplifier with low-impedance output stage, which receives the triangular waveform at the input, uses resistive feedback and produces a triangular current at the output. The mirrored amplifier allows us to achieve maximum swing at the output terminal. The class-AB output stage of the amplifier is designed to provide all the current needed by the sensor. A decoupling stage between the low-voltage and high-voltage blocks is necessary to level shift the triangular wave produced by the low-voltage block around half of the high-voltage power supply.

The two-channel sensor readout circuit is able to measure the outputs of the sensing coils and to process the resulting signal. Each channel of the readout circuit consists of five different blocks. The first block is a gain stage that amplifies each of the two outputs of the sensing coils by a factor of ten. In the second and third blocks the difference between the two outputs is quadrature demodulated by a mixer and amplified again by a factor of six. The fourth block is a 2$^{nd}$-order Sallen-Key low-pass filter that removes all the high-frequency components resulting from the demodulation and returns a DC value that is proportional to the magnetic field, which is then amplified with a programmable gain (from 0 to 100) in the last block. The DC output of the readout chain is finally processed by a 13b ADC and delivered in digital form to the output. A single ADC with a multiplexer for both readout channels is used.

The electronic interface circuit has been fabricated in a 0.35µm CMOS process with two poly and four metal layers. The micrograph of the 1.7mm$^2$ chip is shown in Fig. 21.6.3.

The digital output of the circuit as a function of the external magnetic field applied through Helmholtz coils shown in Fig. 21.6.4. The error with respect to a linear fit is reported in Fig. 21.6.5. The system response is linear in the range of ±60µT, with a maximum non-linearity error of about 3% of full-scale. The sensitivity obtained is 11LSB/µT. All the data collected are consistent with the performance of the sensor by itself as previously measured with dedicated test equipment.

In order to evaluate the performance of the proposed micro-fluxgate sensing system as a compass, the device was rotated in a horizontal plane, while exposing it to the Earth's magnetic field. Fig. 21.6.6 shows the digital outputs for the two axes of sensitivity as a function of rotation angle. The angle error is smaller than 4° and includes signal non-linearity, hysteresis and noise, as well as the inaccuracy of the setup. The most important features of the device are summarized in Fig. 21.6.7.

*References:*
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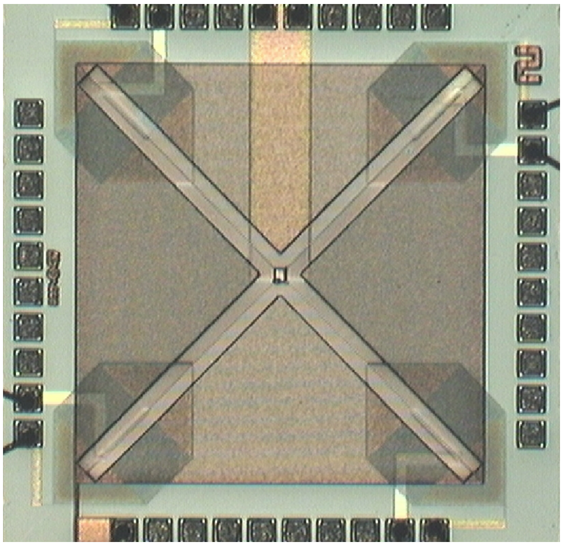

Figure 21.6.1: Micrograph of the micro-fluxgate magnetic-field sensor.

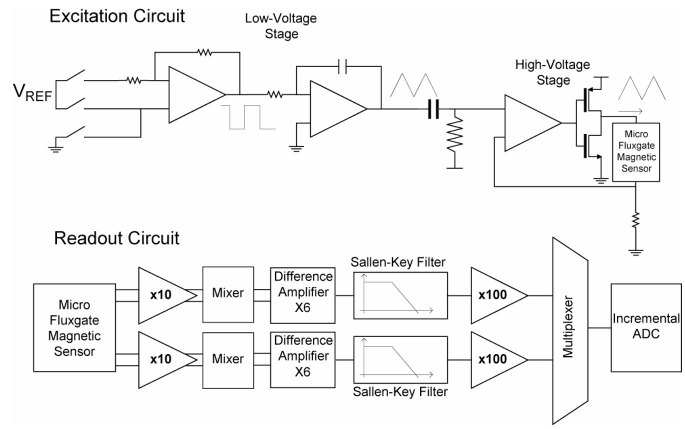


Figure 21.6.2: Block diagram of the integrated interface circuit.

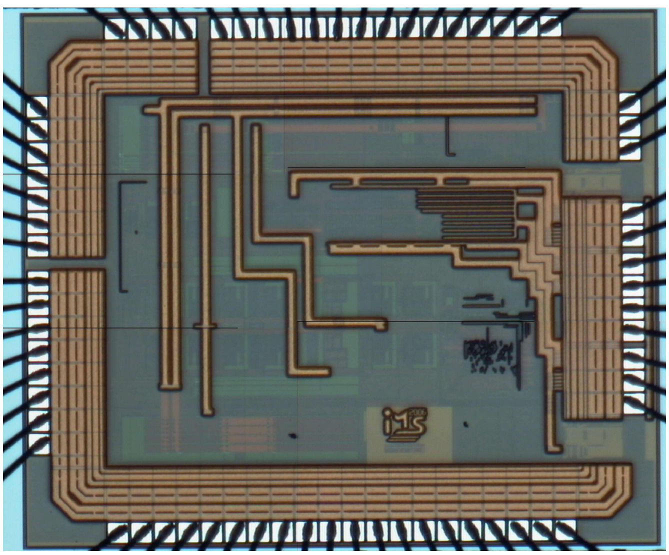

Figure 21.6.3: Micrograph of the integrated interface circuit.

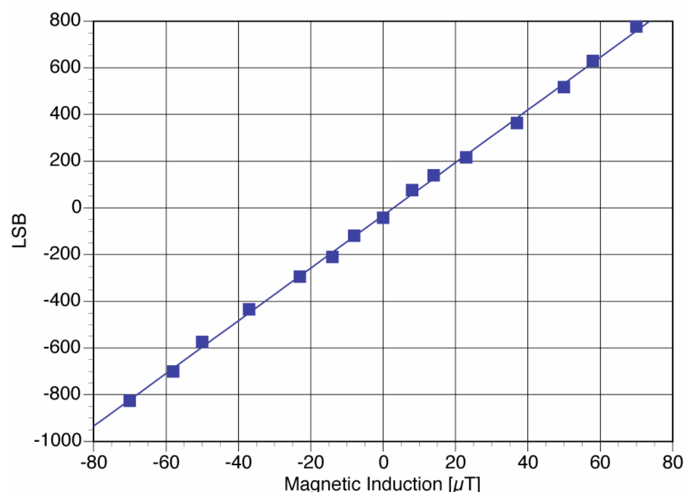


Figure 21.6.4: Digital output of the interface circuit as a function of the applied magnetic induction.

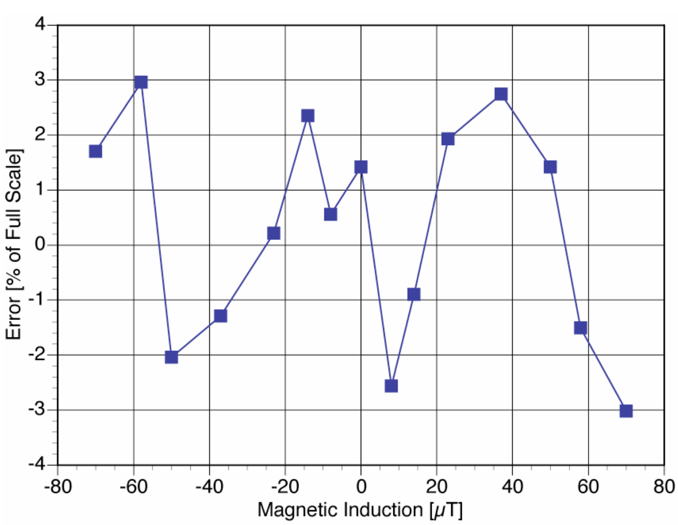


Figure 21.6.5: Linearity error as a function of the applied magnetic induction.

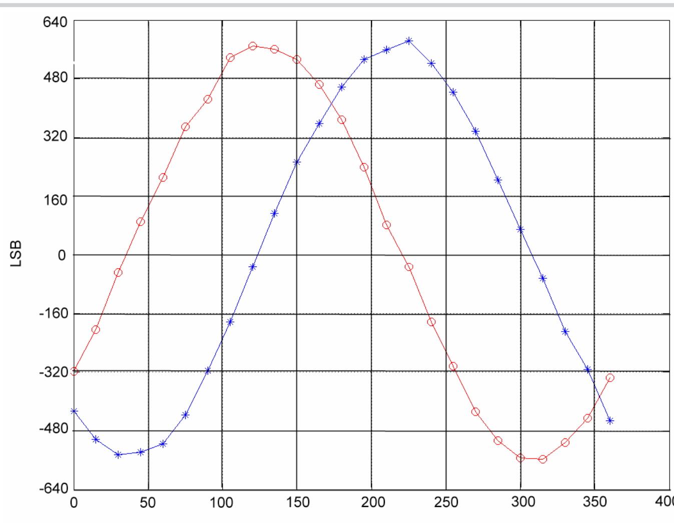


Figure 21.6.6: Digital outputsforthe two axes of sensitivity as a function of rotation angle in the Earth's magnetic field.

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| *Parameter* | *Value* |
|---|---|
| Sensor technology | 0.5µm CMOS |
| Ferromagnetic core | Vitrovac 6025 X deposited by DC-magnetron sputtering |
| Interface circuit technology | 0.35µm CMOS |
| Sensor area | 3.2mm$^2$ |
| Interface circuit area | 1.7mm$^2$ |
| Supply voltage | 3.3V–26V |
| Magnetic field range | ±60µT |
| Linearity error | 3% of full scale |
| Angle error (Earth magnetic field) | 4° |

**Figure 21.6.7: Feature summary.**

 